

# Hipparcos open clusters and stellar evolution

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## ABSTRACT

By relying on recently improved Hipparcos parallaxes for the Hyades, Pleiades and Ursa Major clusters we find that stellar models with updated physical inputs nicely reproduce the location in the color magnitude diagram of main sequence stars of different metallicities. Stars in the helium burning phase are also discussed, showing that the luminosity of giants in the Hyades, Praesepe and Ursa Major clusters appears to be in reasonable agreement with theoretical predictions. A short discussion concerning the current evolutionary scenarios closes the paper.

**Key words:** open clusters and associations:individual:Hyades, Pleiades, Ursa Major, Praesepe, stars: evolution, stars:Hertzsprung-Russell (HR) diagram, stars:horizontal branch

## 1 INTRODUCTION

The comparison of theoretical isochrones with observed Color Magnitude (CM) diagrams of stellar clusters is the most direct method for testing evolutionary theories and for investigating the evolutionary status of cluster stars. In this context, the nearest open clusters have often been selected in the past as privileged targets for testing theoretical predictions. As early as 1963 Iben compared theoretical models with the Hyades and Pleiades CM diagrams and with current estimates of the luminosity-mass relationship. Though written about 40 years ago, certain aspects of the paper are still of interest. The author regarded the overlap of the Hyades and Pleiades Main Sequence (MS) as a risky procedure, due to the possibly different chemical compositions of the two clusters; a point that is still debated in recent papers, as we will discuss later. Moreover he drew attention to the role of superadiabatic convection, noting that there are no reasons for assuming the same mixing length value for stars of different chemical composition, mass or in different evolutionary phases.

At that time, a main source of uncertainty in the comparison between theory and observation was the unknown cluster distance, i.e. the lack of observational constraints on the absolute magnitudes of the stars. Hipparcos trigonometric parallaxes for the members of some nearby open clusters has greatly improved the situation, allowing one to apply more stringent constraints to the theoretical predictions. In a previous paper (Castellani, Degl’Innocenti & Prada

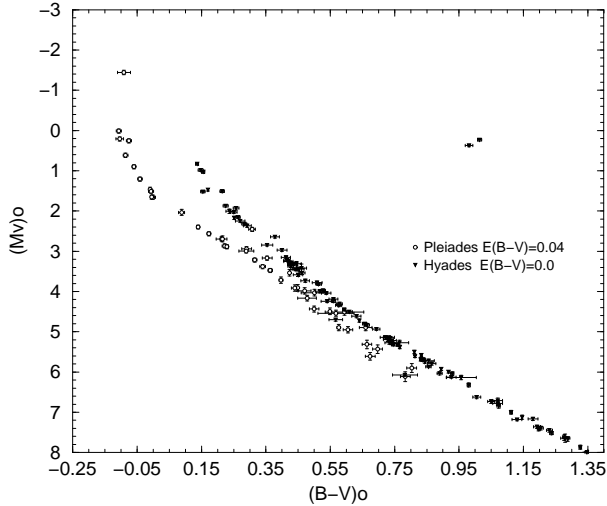
Moroni 2001, Paper I) we compared theoretical isochrones with improved Hipparcos observational data for the Hyades (Dravins et al. 1997, Lindegren et al. 2000), discussing the sources of uncertainties in the theoretical predictions. More recently, Madsen, Dravins & Lindegren (2002) again used radial motions of stars to present CM diagrams of unprecedented accuracy not only for the Hyades but also for other nearby clusters, allowing further useful comparisons with the theoretical scenario. In this work we have selected clusters with low or even negligible reddening estimates, namely the Hyades, Pleiades and Ursa Major, in order to make theoretical predictions on H burning structures at different stellar metallicities. We adopt the parallax of the single stars by Madsen et al. (2002) (see their table 2). Observational data for Praesepe, whose estimated metallicity is the same as that of the Hyades, will be added in Sect.4 to discuss the observational evidence for the helium burning evolutionary phase.

## 2 MAIN SEQUENCE STARS

### 2.1 Hyades and Pleiades

To start our investigation let us first consider the Hyades and Pleiades as clusters having tighter MS, thereby imposing us more severe constraints on the theoretical predictions.

Perryman et al. (1998) first used Hipparcos data to investigate the distance, structure, membership, dynamics and age of the Hyades. In Paper I we adopted Hyades parallaxes



**Figure 1.** CMD for the Hyades and Pleiades clusters, using the parallax values from Madsen et al. (2002). Visual, spectroscopical and suspected binaries are excluded, see also Madsen et al. (2000) for the Hyades and Raboud & Mermilliod (1998) for the Pleiades. The Pleiades data are corrected for the reddening. Error bars indicate observational errors as given by Madsen et al. (2002) for the parallax and by the Hipparcos catalog (at the node <http://astro.estec.esa.nl/Hipparcos/HIPcataloguesearch.html>) for the colors.

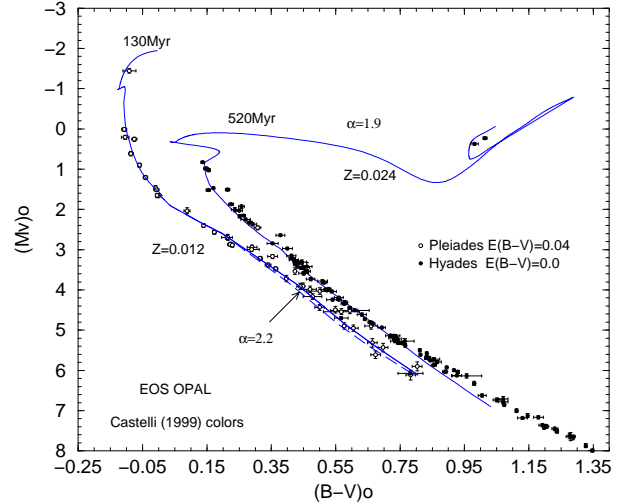
as improved by Madsen et al. (2000) according to their kinematical method. In the present paper we used the latest values given by Madsen et al. (2002); however the differences in the Hyades CM diagram appear to be negligible. Regarding the Pleiades, Madsen et al. (2002) already observed that the kinematics does not improve the Hipparcos parallaxes.

The reddening of the Hyades is generally assumed to be negligible (see e.g. Perryman et al. 1998). As well known, the interstellar medium inside the Pleiades is not homogeneous, thus the cluster is affected by a differential reddening (van Leeuwen 1983, Breger 1986, Hansen-Ruiz & van Leeuwen 1997) which produces a MS slightly scattered. As a first approximation we adopted the commonly accepted average value  $E(B-V) \approx 0.04$  mag (Robichon et al. 1999a, Mermilliod et al. 1997, van Leeuwen 1999a, Pinsonneault et al. 1998, Loktin, Matkin & Gerasimenko 1994 etc.).

By adopting the above quoted values of the reddening and the distance moduli we have drawn the  $(Mv)_o$ ,  $(B-V)_o$  CM diagrams for the two clusters shown in Fig.1; their relative location indicates that the Pleiades stars should have lower metallicity and/or larger helium content.

The aim of this work is to check if suitable theoretical models are able to reproduce the Hipparcos CM diagram for stars of different metallicities. We are mainly interested in the region not affected by external convection, that is a region in which the fit does not depend on the free “mixing length” parameter. As already discussed in Paper I, theoretical temperatures are indeed independent of the efficiency of the external convection only for stars hotter than  $B-V \sim 0.4$  (where the convection vanishes) or cooler than  $B-V \sim 1.2$  (where the convection becomes adiabatic).

As in Paper I, we assume for the Hyades stars  $Z=0.024$  (see e.g. Perryman et al. 1998) together with  $Y=0.278$ , as given by extrapolation of the linear relation between  $Y$  and



**Figure 2.** CM diagram of the Hyades and Pleiades, as in Fig.1, compared with the theoretical isochrones for the Hyades and Pleiades composition ( $Z=0.024$   $Y=0.278$  and  $Z=0.012$   $Y=0.27$ , respectively). The adopted value for the mixing length is  $\alpha=1.9$  in both cases. The position of the Pleiades Zero Age Main Sequence (ZAMS) for a different value of  $\alpha$  is shown as dashed line. Equation of state from Livermore (Rogers et al. 1996) and colour transformations and bolometric corrections from Castelli (1999).

$Z$ , connecting metal poor Pop.II stars ( $Z=10^{-4}$   $Y=0.23$ ) to the original composition of the Sun given by standard solar models (SSM)  $Z=0.02$   $Y=0.27$  (see e.g. Pagel & Portinari 1998, Castellani, Degl’Innocenti & Marconi 1999).

As for the Pleiades, recent estimates (Thevenin 1998, Friel & Boesgaard 1990, Grenon 1999), give  $-0.19 \lesssim [Fe/H] \lesssim 0.03$ . It should be noted that  $[Fe/H]=0$  does not necessarily correspond to the solar metallicity because the  $[Fe/H]$  value also depends on the helium content. Again according to SSM, the present metallicity and helium abundance at the solar surface, after diffusion processes, are estimated to be  $Z \approx 0.017 \div 0.018$   $Y \approx 0.24$ , reproducing the observational value:  $(Z/X)_\odot \sim 0.0230$  (see e.g. Bahcall, Pinsonneault & Basu 2001, Brun, Turck-Chièze & Zahn 1999, Ciacio, Degl’Innocenti & Ricci 1997, Degl’Innocenti et al. 1997). Thus a star with present surface abundance of  $Z \approx 0.02$   $Y \approx 0.27$  shows a value of  $[Fe/H]$  of about 0.06. As discussed below we will adopt the value  $Z=0.012$  for the cluster fit, which is within the observed range of metallicities.

Stellar models were computed with a version of the FRANEC evolutionary code (Chieffi & Straniero 1989; Ciacio et al. 1997), improved so as to account for the most recent input physics (Cassisi et al. 1998), adopting OPAL EOS (Rogers et al. 1996) and using the Castelli (1999, C97) model atmospheres to derive stellar magnitudes in the selected photometric bands (see also Castelli 1998, Castelli, Gratton & Kurucz 1997).

As well known, a decrease of metallicity or an increase of helium shifts the MS toward higher temperatures. Thus to fit observational data one could tune these two values to within reasonable ranges. If one fixes the metallicity at  $Z=0.015$ , to fit observations one would need a helium abundance of  $Y \approx 0.30$ , a value which appears slightly too large. Figure 2 shows our preferred fit for the two clusters, as obtained for

a Pleiades metallicity of  $Z=0.012$ , well within the range of metallicity estimates, with a helium content of  $Y=0.27$ . One finds that theoretical results nicely reproduce observations in all regions excepting the lower end of the Hyades MS; this problem has already been analyzed in Paper I and it will be not discussed here. Interestingly enough, one finds that the portion of the MS affected by external convection can be satisfactorily fitted with the same value of the mixing length parameter ( $\alpha=1.9$ ).

We conclude that the adopted stellar models seem to be able to account for the location of H burning structures even with different metallicities, and that there is no evidence against the adopted evolutionary scenario. The estimated age for the Pleiades appears to be in reasonable agreement with the results of Stauffer et al. (1999) and Ventura et al. (1998); however the range of evolutionary parameters derived in the literature for a given cluster, is an indication of the uncertainty still affecting this kind of procedure.

## 2.2 Ursa Major

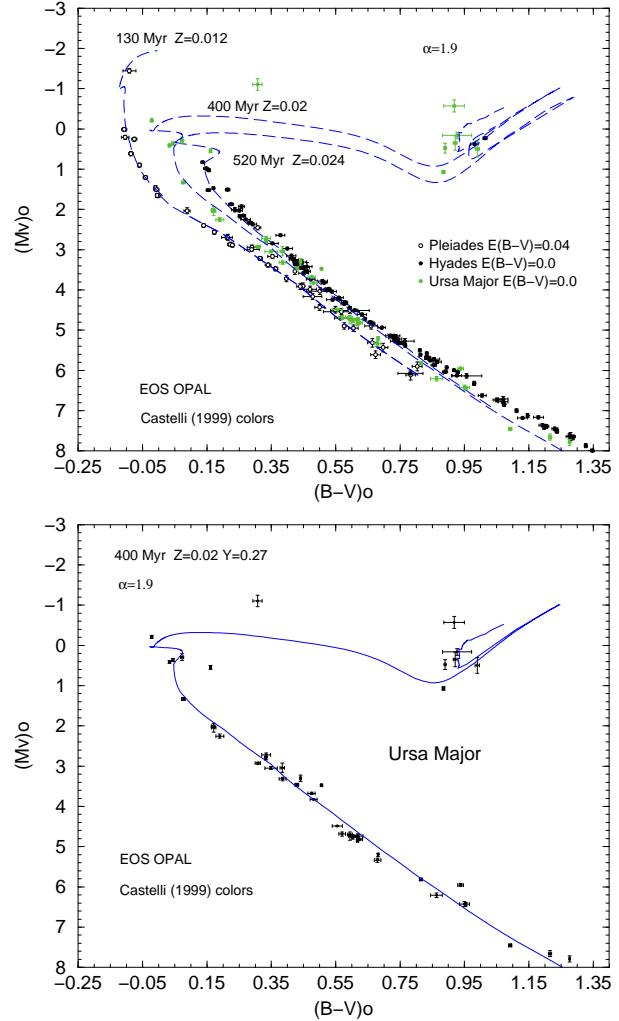
The previous investigation can be usefully implemented with data for the Ursa Major, a cluster which - according to the literature - should have a solar metallicity ( $Z=0.02$ ) and a negligible reddening (Mermilliod 1977). Adopting the photometric data from the Hipparcos catalogue and the trigonometric parallax from the radial velocities given by Madsen et al. (2002), one indeed finds (Fig.3, upper panel) that the Ursa Major MS falls just between the Hyades and Pleiades MS, confirming the quoted metallicity.

Figure 3, lower panel, shows our best fit for the Ursa Major cluster as obtained for  $Z=0.02$ ,  $Y=0.27$  and an age of 400 Myr. The agreement between the observed data and the theoretical isochrones appears to be satisfactory even if the statistic is poor. It may be noted that the phases influenced by the  $\alpha$  value appear to be fitted by the same value of the mixing-length parameter ( $\alpha = 1.9$ ) for all the three clusters.

Before leaving the argument, it is worth noting that present models have all been computed by adopting the classical Schwarzschild criterion for the extension of the convective regions. As well known, the debate is still open about the occurrence of a larger central mixing as given by the core overshooting scenario (see, e.g., Testa et al. 1999, Pols et al. 1998). However, as already shown for the Hyades in Paper I, we found that a similar best fit for all the clusters can be attained with mild overshooting (extra-mixing by  $l_{ov} = 0.25H_p$ ) provided that the cluster age is increased (see e.g. Maeder 1976). The reason is that the two sets of isochrones significantly differ only in the depopulated region of the CM diagram.

## 3 HELIUM BURNING STARS

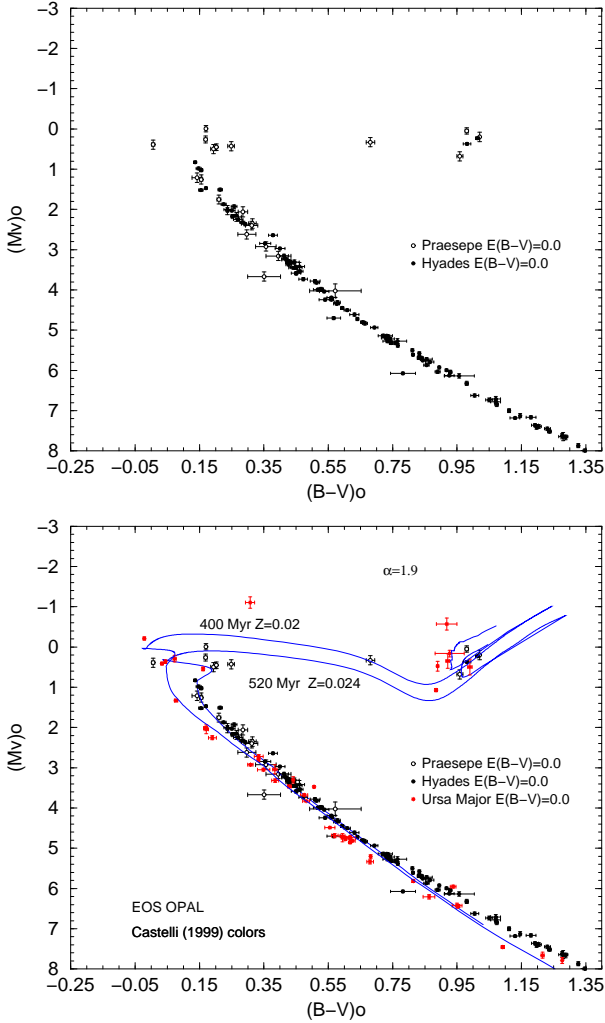
As shown in the previous Figures 2 and 3, both the Hyades and Ursa Major have He-burning stars, though not very abundant. In Paper I we discussed He-burning stars in the Hyades, advancing the suggestion for theoretical models slightly underluminous. This is a relevant point since for less massive stars with degenerate progenitors an opposite tendency has been suggested (see e.g. Pols et al. 1998; Castellani et al. 2000).



**Figure 3.** Upper panel: as in figure 2 with the addition of the fit of the Ursa Major cluster. Lower panel: CMD for the Ursa Major cluster, using the parallax values from Madsen et al. (2002). Visual, spectroscopical and suspected binaries are excluded. Error bars indicate observational errors as given by Madsen et al. (2002) for the parallax and by the Hipparcos catalog for the colors. Present best fit with a 400 Myr theoretical isochrone ( $Z=0.02$   $Y=0.27$   $\alpha = 1.9$ ) is also shown.

However, the sample of Hyades He-clump stars can be improved by adding the data from Praesepe. Indeed metallicity estimates for Praesepe provide values which are compatible with the Hyades metallicity (see e.g.  $[Fe/H] = 0.135 \pm 0.07$  by Boesgaard & Budge 1988,  $[Fe/H] = 0.17 \pm 0.01$  by Grenon 1999). Such a similarity is supported by the similar CM diagram location of the two MS, as shown in Figure 4 where Praesepe data are plotted taking the photometry from the Hipparcos catalogue, the trigonometric parallax from Madsen et al. (2002) and assuming a negligible reddening (Mermilliod et al. 1997, Robichon et al. 1999a, Pinsonneault et al. 1998, van Leeuwen 1999a).

Figure 4 also shows that the two clusters have quite similar star distributions all over the CM diagram, supporting not only a similar metallicity but also a similar age, allowing one to adopt the He-burning stars as a unique common sample. The number of stars in the He-burning clump remains



**Figure 4.** Upper panel: CMDs for the Hyades and the Praesepe clusters, using the parallax values from Madsen et al. (2002). Visual, spectroscopical and suspected binaries are excluded. Error bars indicate observational errors as given by Madsen et al. (2002) for the parallax and by the Hipparcos catalog for the colors. Lower panel: CMDs for the Hyades, Praesepe and Ursa Major clusters and the relating isochrones.

rather small, not allowing us to make precise constraints on the theoretical models. However, with this caveat in mind, Fig. 4 (lower panel) now seems to suggest a general agreement between the theory and the observational data, casting serious doubts on the suspected underluminosity of the models.

Interestingly enough, one also finds that the Ursa Major He-clump not only appears to be in fair agreement with the theoretical predictions but that it also appears to be brighter (on the average) than those of the Hyades and Praesepe, as predicted by theory as a consequence of the lower age. Unfortunately the He-clump is quite spread out, so that the observational constraints are not as stringent as one would wish. The only conclusion that can be safely drawn is that there is a general agreement between the theory and observation even though further investigations are needed. Incidentally, we recall that the situation is not changed by the adoption

of a mild core overshooting during the main sequence phase (see e.g. Paper I for a discussion).

## 4 DISCUSSION AND CONCLUSIONS

To conclude the paper it may be worth recalling briefly the debate concerning the Pleiades CM diagram. In recent years, several authors, assuming for the Pleiades a solar metallicity (see e.g. Mermilliod et al. 1997, Pinsonneault et al. 1998), found a disagreement between the models and the Hipparcos data. To account for such a disagreement, Pinsonneault et al. (1998) suggested the possibility of localized systematic errors in the Hipparcos parallaxes of the order of 1 mas for open clusters and stellar associations. The disagreement was quite recently confirmed by Stello & Nissen (2001) on the basis of Strömgren photometry of F-type stars.

Narayanan & Gould (1999) used Hipparcos proper motions to further investigate the parallaxes of Pleiades stars, finding a distance modulus with a rather large error ( $\pm 0.18$  mag.) which they claimed to be in disagreement with that derived directly from Hipparcos parallaxes and in agreement with that obtained through MS fitting. However, the uncertainty is of the same order as that of the quoted discrepancy. Thus the authors suggested the possibility of systematic errors due to spatial correlations over small angular scales.

This possibility was rejected by Robichon et al. (1999a,b) and van Leeuwen (1999b) who, on the basis of a range of statistical checks on the data and an evaluation of data reduction methods, excluded the occurrence of systematic errors (see also van Leeuwen & Evans 1998). Moreover Stello & Nissen (2001) quoted the recent photometric determination of the Pleiades metallicity by Grenon (1999) based on about 62 stars:  $[\text{Fe}/\text{H}] = -0.11 \pm 0.025$  showing that with this choice of metallicity the Pleiades ZAMS is fitted successfully, as supported and confirmed by the present investigation.

We conclude that, if the metallicities adopted in this work will be confirmed by future investigations, theoretical models appear to be consistent with observations and there are no reasons for claiming the existence of errors either in the Hipparcos results or in the theoretical predictions. At the present status of the art, uncertainties in the chemical composition of the Pleiades are larger than uncertainties in the Hipparcos parallaxes and thus, in our opinion, it is more reasonable to search for the Pleiades composition within plausible ranges of metallicities, as we did, rather than to follow the opposite procedure (see Lebreton 2001 for a discussion).

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